

NACA RM E51J29

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RESEARCH MEMORANDUM

PRELIMINARY RESULTS OF CYCLICAL DE-ICING OF A
GAS-HEATED AIRFOIL

By V. H. Gray, D. T. Bowden, and U. von Glahn

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FOR REFERENCE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

January 24, 1952

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SUMMARY

An NACA 65₁-212 airfoil of 8-foot chord was provided with a gas-heated leading edge for investigations of cyclical de-icing. De-icing was accomplished with intermittent heating of airfoil segments that supplied hot gas to chordwise passages in a double-skin construction. Ice removal was facilitated by a spanwise leading-edge parting strip which was continuously heated from the gas-supply duct.

Preliminary results demonstrate that satisfactory cyclical ice removal occurs with ratios of cycle time to heat-on period (cycle ratio) from 10 to 26. For minimum runback, efficient ice removal, and minimum total heat input, short heat-on periods of about 15 seconds with heat-off periods of 260 seconds gave the best results. In the range of conditions investigated, the prime variables in the determination of the required heat input for cyclical ice removal were the air temperature and the cycle ratio; heat-off period, liquid water content, airspeed, and angle of attack had only secondary effects on heat input rate.

INTRODUCTION

The protection of wings and tail surfaces for high-speed, high-altitude turbojet-powered aircraft by local heating of the areas subject to icing may be accomplished by either continuous heating or cyclical de-icing. In continuous heating, the surfaces are either raised to a temperature just sufficient to maintain the impinging water in a liquid state or are supplied sufficient heat to evaporate all the impinging water in a specified distance behind the impingement area. Past NACA research has provided basic criteria for use in the design of continuous heating systems (references 1 and 2); however, the exact type of continuous heating for an airplane component depends on a complexity of parameters and is more fully discussed in reference 3. Design analysis in reference 3 has shown that the heat requirements and associated airplane performance penalties for high-speed, high-altitude transport aircraft using continuous heating for icing protection are extremely large and in some cases may be prohibitive.

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Another method by which icing protection for airfoil shapes can be accomplished is by cyclical de-icing in which some ice is permitted to form on the surfaces and then is removed periodically during short, intensive applications of heat. A water film between the surface and the ice is caused by the heat application and permits removal of the ice by aerodynamic forces. Because the heating is intermittent, heat is supplied successively to relatively small surface areas; a constant heat load is thus maintained on a heat source. The total heat input for cyclical de-icing, therefore, can be greatly reduced from that required for continuous heating.

Because ice formations normally extend over the leading edge and onto both upper and lower surfaces, removal by aerodynamic forces is slow and erratic even though sufficient heat has been applied to form a water film beneath the ice. The need for a continuously heated parting strip near the leading edge of airfoils is indicated in reference 4 and unpublished NACA data. When an ice-free strip is maintained spanwise along the leading edge, the ice formation is divided into two segments, one each on the upper and lower surfaces of the airfoil, and removal by aerodynamic forces is facilitated.

Previous investigations of cyclical de-icing including analytical studies (references 4 to 9) have been restricted to the use of electric power as a heat source. An electrical system, however, has the inherent disadvantages of large system weight, susceptibility to failure by damage to the heating circuits, high cost in maintenance, and fire hazard when the system fails because of the heater burn-out. In addition, reference 3 indicates that for a high-speed, high-altitude turbojet-powered airplane the most economical icing protection system with respect to installed weight consists of a system utilizing hot gas from a convenient heat source, namely, the turbojet-engine compressor. If the large heating requirements associated with continuous hot-gas heating (reference 3) can be reduced by use of a hot-gas cyclical de-icing system while the low installed weight is maintained, the airplane performance penalties could be decreased from those incurred with the continuous heating system. A hot-gas cyclical de-icing system has the further advantages of integral design with the aircraft structure, low maintenance costs, and elimination of a possible source of aircraft fires.

The NACA Lewis laboratory is currently engaged in an investigation to evaluate the possibilities of the use of a hot-gas cyclical de-icing system for airfoils. The studies are being conducted to determine the requirements for hot-gas cyclical de-icing in terms of the heating and cycle timing necessary for successful operation of such a system and also to obtain the relation between heating requirements, meteorological conditions, and aircraft operating conditions.

The preliminary results presented herein were obtained from an investigation at the NACA Lewis laboratory of an 8-foot chord NACA 65₁-212 airfoil model employing a hot-gas cyclical de-icing system. A continuously gas-heated parting strip near the stagnation region is incorporated in the design of the system to facilitate ice removal. The remainder of the airfoil leading edge is intermittently heated by gas flow through chordwise passages in a double-skin construction similar to that utilized for continuous gas-heating.

The airfoil model was investigated over the following range of icing and operating conditions:

Angle of attack, deg	2 to 8
Airspeed, mph	180 and 280
Liquid-water content, g/m ³	0.3 to 1.2
Datum air temperature, °F	-11 to 20
Gas inlet temperature, °F	200 to 510

DESIGN CONSIDERATIONS FOR HOT-GAS CYCLICAL DE-ICING SYSTEM

Analysis of the problems associated with the design of a hot-gas cyclical de-icing system for airfoils indicates that the following criteria should be considered:

1. The surface area to be de-iced should be divided into a number of segments such that the total number of segments heated in sequence will equal the cycle ratio (total cycle time divided by heat-on period). In this manner, a constant heat load will be maintained.
2. The gas supply duct should be maintained at an elevated temperature level to avoid undue thermal lag in the system.
3. A continuously heated parting strip should be provided near the leading edge in order to obtain consistent and rapid ice removal during cyclical de-icing.
4. In order to insure good ice removal and prevent ice-bridging between the various intermittently heated segments, chordwise parting strips may be desirable.
5. Insulation for the gas supply system may be desirable to reduce heat losses.

DESCRIPTION OF MODEL

General Features

A unique solution to the preceding criteria is obtained by the hot-gas cyclical de-icing system shown in figure 1. The system consists of the following principal features:

1. The gas supply system consists of a double-passage duct in which high-temperature, high-pressure gas will flow outboard in a forward passage and return in a contiguous rearward passage. Throttling valves are located in the rearward passage at each of the airfoil segments to be intermittently heated. These valves are opened in spanwise sequence and thereby permit a constant flow of gas through the forward passage. The constant flow maintains the entire duct continuously heated; consequently, thermal lags in the system become negligible.

2. An ice-free spanwise parting strip near the airfoil leading edge is heated by a conductive fin connecting the outer skin with the forward passage of the gas supply duct. Because the gas supply duct is continuously heated, heat will be conducted through the fin to form a narrow, continuously heated parting strip. The width of the parting strip is governed by the operational and icing conditions; a narrow parting strip of about 0.5 to 1.0 inch is satisfactory for good ice removal and for heat economy.

Other methods for attaining a parting strip are by electric heating or by a hot-gas supply duct independent of the one supplying the intermittently heated segments. An electrically heated parting strip has all the inherent disadvantages of an electrical system, while an independent gas supply duct for the parting strip has weight disadvantages and may incur considerable heat losses.

3. Chordwise ice-free parting strips are located between adjacent intermittently heated airfoil segments. The parting strips are continuously heated by the gas supply duct in a manner similar to that used for the spanwise parting strip.

Details of Model and Apparatus

The model investigated is an NACA 65₁-212 airfoil section of 8-foot chord spanning the 6-foot vertical height of the Lewis icing research tunnel (fig. 2). The leading edge consisting of three spanwise segments is gas-heated to 12 percent of chord. The center segment of the wing is 3 feet in span and contains most of the instrumentation while the top and bottom segments are each 1.5 feet in span. All segments are capable of being heated independently for cyclical ice removal.

The heat source used in this investigation consisted of high-pressure heated air, the temperature of which was regulated by additions of cold air and the flow was regulated by a pressure-regulating valve. The heated air was metered by a standard orifice installation in the supply line leading to the airfoil model.

The gas heating system within the airfoil leading edge had two principal components: the pressurized steady-state system, and the low-pressure intermittent heating system used for cyclic de-icing of the surfaces of successive spanwise segments. Specific component dimensions are summarized in table I.

Steady-state system. - The hot-gas supply duct consists of a relatively small thick-wall double-passage aluminum duct (fig. 1). The duct is mounted semirigidly inside the airfoil leading edge and thus facilitates a spanwise movement when the hot-gas flow expands the duct. Along the rearward passage are located throttling valves, one at the center of each of the three intermittently heated airfoil segments. Because the span of the airfoil is only 6 feet, the proper number of spanwise segments cannot be provided; hence, a fourth valve is provided at the exit end of the return passage and, when open, represents all the additional segments used in an actual long-span wing. The supply duct is insulated and isolated from all wing structure except where finning is attached to provide heat for parting strips.

The aluminum fin used to conduct heat from the double-passage supply duct to the stagnation region is designed to provide the required temperature gradient necessary for adequate heat transfer. In the model investigated, the fin was approximately 3.5 inches long and 0.062 inches thick. For convenience in model assembly and to account for thermal expansion of the supply duct, the fin was made in two parts; proper contact was insured by screws which held the two sections of the fin together and maintained a sliding contact at the joint (fig. 1).

The outer skin of the airfoil is made of 0.025-inch-thick aluminum alloy in order to provide a high temperature gradient in the skin adjacent to the conductive fin; an ice-free parting strip of the desired width is thereby obtained. Strength and rigidity of the leading edge is provided by an inner skin of 0.040-inch-thick aluminum alloy corrugated with a 1-inch spanwise pitch, the corrugations of which provide chordwise gas passages of 0.125-inch height. Chordwise parting strips at the ends of the center segment are similar to those used for the spanwise parting strip except that the fins do not have slip joints. Dimensions of the chordwise parting-strip fins are given in table I.

Instrumentation in the steady-state system is as follows:

(1) Gas-temperature thermocouples in both passages of the supply duct at 5 spanwise locations,

(2) Static pressure tubes adjacent to the gas temperature thermocouples in the supply duct,

(3) Thermocouples at several locations along the supply duct to determine metal wall temperatures,

(4) Thermocouples in pairs in the spanwise fin and in one set of chordwise fins to determine temperature gradients.

Intermittent heating system. - Entrances to the passages formed by the outer skin and the corrugated inner skin are located near the spanwise parting strip on both top and bottom surfaces of the airfoil (fig. 1). The passages extend to approximately 12 percent of chord. After leaving the passages, the gas is permitted to exhaust through the aft regions of the airfoil and to exit through a slot at the trailing edge. Bulkheads at the ends of the center segment are insulated to reduce spanwise heat losses during the heat-on period. Asbestos sheeting, which is also used to insulate the corrugated inner skin in the plenum chambers, allows the gas to exert the maximum heating near the leading edge where the ice formations are largest. Solenoid-controlled, compressed-air-actuated valves were used to operate the intermittently heated sections, while electric timers were used to control the heating and icing periods for each segment.

Instrumentation in the intermittent heating system was as follows:

(1) Gas temperature thermocouples in the plenum chambers and inside the chordwise gas passages at six chordwise and four spanwise points,

(2) Surface temperature thermocouples at 21 points chordwise around the center segment leading edge and at five other spanwise cross sections,

(3) Thermocouples to measure metal temperatures at various points such as ribs, front spar, inner-skin corrugations, and beneath insulation,

(4) Static pressure taps in the three plenum chambers and in the airfoil afterbody.

EXPERIMENTAL CONDITIONS AND TECHNIQUES

In the design of the present airfoil model, an operational and icing condition was selected as follows:

Datum air temperature, °F	0
Airspeed, mph	280
Liquid-water content, gram/cu m	0.6
Airfoil angle of attack, deg	5
Supply-duct inlet gas temperature, °F	500

These operational and icing factors were selected on the following bases: the combination of liquid-water content and air temperature were deemed to constitute an extremely severe icing condition (reference 3); the airspeed selected is the maximum attainable in the icing research tunnel at all the angles of attack to be used in the investigation; the angle of attack of 5° , together with the airspeed, was chosen as being representative of low cruise attitude for a turbojet-powered aircraft and also to provide a relatively large area of droplet impingement on the airfoil; finally, the gas temperature was selected to represent the temperatures now being attained at turbojet-engine compressor outlets.

The de-icing performance of the airfoil also was evaluated over the following range of off-design icing and operating conditions:

Datum air temperature, $^\circ\text{F}$	-11 to 20
Liquid water content, gram/cu m	0.3 to 1.2
Airspeed, mph	180 and 280
Supply duct inlet gas temperature, $^\circ\text{F}$	200 to 510
Angle of attack, deg	2, 5, and 8
Heat-off period, min	4 to 10

For convenience in evaluating the de-icing performance in off-design condition, the greater part of the investigations were made with the following nominal conditions:

Datum air temperature ($^\circ\text{F}$)	Liquid water content (gram/cu m)	Air speed (mph)
-10	0.6	280
0	.6	180, 280
10	.6	280
20	.8	180, 280

The angle of attack was nominally set at 5° and the heat-off period at 260 seconds.

Datum air temperature was defined and determined as the surface temperature of the unheated airfoil in icing conditions. Little difference between total and datum air temperature was found for the conditions investigated.

The heat input rates necessary for consistent and rapid ice removal from the airfoil were determined by progressively adjusting the heat-on time for a given heat flow rate and icing condition until visual observation indicated satisfactory operation of the system.

Data recorded included: gas flows; gas temperatures in the span-wise gas supply duct, in the plenum chambers, and in the chordwise

corrugated passages; surface temperatures in the airfoil skin; metal temperatures in the spanwise and chordwise continuously heated fins, and in the leading-edge structure; and static pressures in the leading-edge regions. The icing conditions were determined from a previous calibration of the tunnel.

Throughout the studies, photographs of the ice formations before and after heat application were taken to record the effectiveness of ice removal and the magnitude of residual and runback ice formations.

RESULTS AND DISCUSSION

System Performance at Design Condition

The over-all performance of the system for the design condition was found to be satisfactory at a gas flow of 800 pounds per hour, a heat-on period of 15 seconds, and heat-off period of 260 seconds. Under these conditions, the parting strip was approximately 0.75 inch wide after 258 seconds of icing (fig. 3(a)). The heavy ice formations at the leading edge were removed after 4 to 8 seconds of heating. Ice removal occurred first on the top surface while the ice on the lower surface shed progressively aft from the parting strip. At the end of the heating period (fig. 3(b)), no ice remained on the heated area with the exception of small deposits on the last 4 inches of the heated lower surface (9 to 13 in. aft of leading edge). In this region, which is just rearward of the plenum chamber partition, runback rivulets occasionally froze and remained for two or three cycles before the larger accretions were removed.

Pertinent system operational data obtained for satisfactory performance at the design condition are as follows:

Cycle ratio (total cycle time divided by heat-on period)	18.3
Heat flow to center segment during heat-on period (gas flow times specific heat times differential between plenum inlet and total air temperature, Btu/hr)	89,000
Equivalent continuous heat flow to center segment (heat flow divided by cycle ratio), Btu/hr	4850
Equivalent continuous heat per foot of span, Btu/hr	1615
Equivalent continuous heating per square inch of heated area, watts	1.6
Parting-strip surface temperature before heat-on, °F	55
Parting-strip-fin temperature gradient, °F/in.	61
Parting-strip-fin heat flow per foot of span, Btu/hr	480

The gas temperature and pressure distribution in the double-passage supply duct are listed subsequently for various station numbers denoting

the distance in inches from the model inboard end (floor of tunnel, fig. 2). All the pressures are static pressure differentials above the static pressure of 25.86 inches of mercury in the tunnel during the center-segment heat-on operation.

Station	Gas temperature in duct (°F)		Pressure in duct (in. Hg)	
	Front	Rear	Front	Rear
6	509	462	16.3	10.3
18	506	464	15.9	10.3
36	496	467	15.0	7.7
54	487	---	14.0	9.9
68	481	469	13.5	9.5

The static pressure in the center plenum chamber during gas flow was 6.8 inches of water. The values are of particular interest in the design of flow passages for intermittently gas-heated airfoils.

The reduction in gas temperature along the forward passage of the duct was rather uniform at 5.5° F per foot of span and the gas temperatures in the return passage remained essentially constant. A sizable drop in temperature and pressure occurred at the 180° turn in the passage. The total gas temperature drop was approximately 7° F per foot of span.

Cyclical De-Icing at Off-Design Conditions

De-icing performance criterion. - Marginal heating requirements for cyclical de-icing under widely varying conditions are difficult to establish with a uniform degree of accuracy. Considerable leeway exists in determining the required heating rates due to the transient factors involved. Ice removal first occurs near the leading edge where the heating rate is greatest, and the remainder of the ice sheds progressively from fore to aft as the surface temperature rises above freezing. When the gas flow, gas temperature, or heating period is increased, the surface location where the peak temperature reaches 32° F moves progressively farther aft and water runback refreezes behind this point. As an aid in establishing a uniform degree of de-icing protection for various conditions, therefore, the following visual criterion was adopted: ice removal should be complete over the whole heated leading edge and top surface; the lower surface should be ice-free to at least 9 percent of chord; and during icing, the parting strip should remain ice-free to facilitate ice removal by aerodynamic forces.

Under some conditions runback on the lower surface refreezes at the rear of the heated area and gradually builds up in size. If this runback

is allowed to freeze upon the heatable area, secondary ice shedding occurs during subsequent heating cycles as the ice pieces grow and are subject to larger aerodynamic forces. The series of photographs in figure 4 illustrates this secondary ice-removal action over a period of 51 minutes, during which the heat-on period was 15 seconds and the heat-off period approximately 6 minutes. The residual ice is shown in figure 4(j) after the heat-on period was increased to 20 seconds for two cycles. An example of the effect of a variation of heat-on period on the de-icing performance is shown in figure 5, wherein the lower surface is shown after 1 hour and 22 minutes of cyclic ice removal with a 20-second heat-on period followed by 33 minutes during which the heat-on period was 15 seconds; the heat-off period was 6 minutes in each case. Heavier residual ice was seen after the 15-second heat-on period, although the location of the ice was essentially the same as that remaining after the 20-second heat-on cycles.

In the following sections are presented the effects of several icing and operational variables upon the airfoil cyclic heating requirements based on the foregoing criterion.

Angle of attack. - Impingement characteristics and heating requirements of the airfoil were investigated over a range of angles of attack from 2 to 8°. At an angle of attack of 2°, impingement on the unheated airfoil was confined to the leading-edge region. A heavy deposit of ice was formed approximately 2 inches in total chordwise width with very little icing on the lower surface aft of the parting strip (fig. 6(a)). At an angle of attack of 8°, heavy icing occurred toward the upper-surface side of the parting strip for approximately 1 inch and on the lower surface for approximately 3 inches, followed by an additional 3 inches of thin, irregular ice deposition. At an angle of attack of 5°, the impingement approximated the 8° deposition in general but was confined more toward the leading-edge region (fig. 6(b)).

The ice-removal characteristics also varied greatly with the airfoil angle of attack. At low angles of attack the small amount of ice aft of the parting strip was usually removed before the heavy leading-edge ice. At the high angles of attack the leading-edge and top-surface ice was removed first, while the lower-surface ice shed progressively from front to rear, partly by shedding and partly by melting and sliding back along the surface. With large impingement rates (especially at high datum air temperatures) and at high angles of attack, the lower-surface residual ice near the end of the heated area protruded into the air stream sufficiently to be subject to direct impingement. This impingement on residual ice formations resulted in a spanwise line of irregular ice pieces which shed sporadically.

Although the icing and ice-removal characteristics of the airfoil varied with angle of attack, the heat requirements for good removal were found to be essentially independent of angle of attack.

The effect of the parting-strip location on removal characteristics was not investigated; however, unpublished NACA data indicate that for good ice removal the parting strip should be moved nearer the chordline with decreasing angles of attack.

Liquid-water content and icing time. - The size of ice formations before removal is determined by the liquid-water content and the icing period together with the airspeed, air temperature, angle of attack, and droplet size. The available data indicate that an increase in the liquid-water content requires a small increase in the heat-on period as shown in figure 7 for four conditions. A similar increase in the heat-on period occurs with an increase in the heat-off period (fig. 8). The length of the icing period for cyclical de-icing cannot be determined exactly because data are not available on the specific drag and airplane performance losses caused by icing of airfoils. Unless otherwise specified, an icing or heat-off period of approximately 260 seconds was used hereinafter for all de-icing conditions. The ice formations so obtained were considered to be of small detriment to aircraft performance. The largest ice formations obtained in the 260-second icing period, which occurred at a datum air temperature of 20° F, an airspeed of 280 miles per hour, and a liquid-water content of 1.0 gram per cubic meter, were approximately 0.6 inches in maximum thickness at the leading edge.

Gas-flow rate. - The variation of required heat-on period is shown in figure 9 as a function of gas flow for various operating and icing conditions. A significant reduction in the heat-on period occurred with an increase in the gas flow. For example, at an airspeed of 180 miles per hour, a datum air temperature of 0° F, and a plenum-inlet-gas temperature of 460° F, an increase in gas flow from 530 to 810 pounds per hour reduced the heat-on period from 30 to 10 seconds. The heavy leading-edge ice was removed in a fraction of the heat-on periods shown in figure 9, but the rear part of the lower surface took longer to de-ice, as discussed previously. The gas temperature at the rear end of the chordwise passages remained higher at high gas flows than at a low gas flow, and ice removal over the heated area occurred at more nearly the same time.

Plenum-inlet-gas temperature. - The effect of plenum-inlet-gas temperature on heat-on period is shown in figure 10 for several operating and icing conditions. Similar to the effect of gas flow, a marked decrease in heat-on period occurred with an increase in gas temperature, although the reduction in heat-on period with gas temperature was not so rapid percentagewise in the range investigated as with a change in gas flow.

Datum air temperature. - The effect of datum air temperature on the heat flow required to de-ice the 3-foot span center segment of the model is shown in figure 11 as a function of heat-on period for two airspeeds and the range of gas temperatures and gas-flow rates investigated. The

heating requirement for any specific heat-on period appears to be primarily a function of datum air temperature; airspeed had only a secondary effect. For the same heat-on period the heat flow required at a datum air temperature of 0° F was approximately double the heat requirement at 20° F. A decrease in the heat-on period increased the heat requirement at any particular datum air temperature and airspeed, as shown by the approximate doubling of the required heat flow during the heat-on period when the period was decreased from 30 to 10 seconds.

Effect of airspeed and cycle ratio. - The effect of airspeed on the center-segment equivalent-continuous heat requirement is shown in figure 12 as a function of datum air temperature for various cycle ratios. A comparison of the heat requirement at a datum air temperature of 0° F and a cycle ratio of 20 indicates that about 13 percent less heat for ice removal is required at 180 miles per hour than at 280 miles per hour. At a datum air temperature of 20° F, however, approximately equal quantities of heat for ice removal are required for the two airspeeds studied.

In figure 12 it is also shown that as the cycle ratio is increased, the heat requirements are decreased. In addition, the heat requirements at a particular cycle ratio increase with a decrease in datum air temperature.

A convenient method of presenting the savings that may be achieved by cyclical de-icing is illustrated in figure 13 in which the equivalent continuous heating requirement is shown as a function of cycle ratio for various airspeeds and datum air temperatures. In lieu of exact data defining the heat requirements for a continuously heated airfoil, estimates were made, from a few preliminary studies of continuous heating of the test airfoil, which indicated heat requirements in the order of 12 to 14,000 Btu per hour would be required at a datum air temperature of 20° F. These values, however, would not result in complete evaporation of the impinging water within the confines of the heated area, and considerable runback refreezing would occur. The heat requirements for cyclical de-icing are seen to decrease rapidly with an increase of cycle ratio from 1 to 16 and then the curves become asymptotic to finite values of heat input. In the selection of a cycle ratio for an airfoil, the number of segments into which the airfoil can be divided and the tolerance of the airfoil to icing during the heat-off period must be considered as well as the reduction in heat input. Therefore, no general statement can be made as to which cycle ratio is most desirable or economical.

Surface and Gas Temperatures during Cyclical De-Icing

Typical surface-temperature-rise curves as a function of time are shown in figure 14 for various chordwise locations. An inflection occurs

at about 32° F in the temperature-rise curves during the heat-on period when ice melting begins. This inflection, however, does not necessarily indicate ice removal, because the entire surface under a given ice formation does not reach 32° F simultaneously. Formation of ice on the lower surface during the heat-off period is shown in figure 14(a) by a flattening of the cooling curve at about 32° F.

Because the gas cools as it proceeds through the chordwise passages, the temperature-rise rate should decrease with increasing chordwise distance. In addition, the point in time at which the surface temperature reaches 32° F should increase with an increase in passage length. Initial temperature-rise rates varied from about 23° F per second near the leading edge to 6° F per second midway on the lower-surface heated area.

Typical variations of peak-temperature-rise values obtained during heat-on periods are shown in figure 15 as a function of chordwise surface distance. In general, the shapes of the curves are similar for all operating and icing conditions noted on the figure. Increases in peak-temperature-rise values occurring at about 9 percent of chord are attributed to heat conduction to the skin from the spanwise partition in the plenum chamber (see fig. 1). For a given gas flow, gas temperature, and air speed, the variation in the level of the surface temperature required for ice removal appears to be changed primarily by the differences in datum temperature; the higher datum temperatures, however, required shorter heat-on periods. The peak-gas-temperature-rise values in the chordwise gas passages are also shown in figure 15 as a function of passage length. It is apparent that the peak temperatures decrease rapidly with increasing chordwise distance, especially on the upper surface of the airfoil. A comparison of the peak surface temperatures as a function of change in gas temperature is shown in figure 16. A decrease in gas temperature is accompanied by an increase in the heat-on period if all other variables are maintained constant. Although small local changes in peak temperature do occur, the curves, in general, are similar in shape and temperature level.

The peak surface temperature rise as a function of chordwise surface distance is shown in figure 17 at an airspeed of 180 miles per hour for two values of heating rate. The temperature-rise values associated with a 12-second heat-on period and a high gas flow are somewhat lower than those obtained with a 25-second heat-on period and a low gas flow.

Parting Strip Requirements

Because the parting strips were continuously heated, they were considered separate from the cyclical ice-removal requirements. As mentioned in the discussion of the design condition, the gas-temperature drop in the front passage of the supply duct was relatively uniform, the temperature

in the rear passage was essentially constant, and a sizeable decrease in temperature occurred at the 180° turn in the supply duct. In lieu of a complete analysis of the heat transfer and losses in the supply duct, the drop in gas temperature from the duct-inlet station to the center-segment valve will be chargeable to the parting strips for a span length of 6 feet. The gas-temperature decrease in the supply duct is shown in figure 18 as a function of gas flow and is expressed in terms of temperature drop per foot of span per 100° F differential between gas temperature and datum air temperature. Every condition and variable investigated is included in figure 18, which accounts for the considerable scatter in data. The curve, however, is defined with fair accuracy and within the limits investigated can be generally applied. For airfoils with longer spans, the gas-temperature drop in the duct calculated on this basis will be conservative, because the temperature loss in the 180° turn will be disproportionately magnified.

The ice-free width of the parting strip varied with the operating and icing conditions. With increasing icing time, the ice-free strip became gradually narrower, but generally did not bridge over because the center of the strip at the fin base was much hotter than the edges. Water flowed spanwise in the valley between the ice formations and was blown out of the valley at several points to form glaze ice formations. These ice formations build outward from the surface on both sides of the parting strip and, in severe cases, bridge over. This ice bridging is accentuated by the vertical mounting of the airfoil, which permits much larger quantities of water to run a greater spanwise distance in the parting strip valley than would normally be encountered on an airplane wing. In all cases where ice bridging of this nature occurred, no adverse effect on time required for ice removal was observed.

The width of the parting strip is also determined by the gas and datum temperatures, and the airspeed. These factors determine the temperature gradient in the airfoil skin in a direction away from the base of the fin. The change in width of the parting strip when the supply-duct-inlet gas temperature was changed from 350 to 500° F is shown in figure 19 for otherwise similar conditions. The width of parting strip obtained with the higher gas temperature was greater than that required for good ice removal. The surface temperature at the parting strip during icing ranged from 40 to 60° F, most of the data averaged about 50° F.

With the integral hot-gas system investigated, it was difficult to confine the parting strip to a narrow region for datum air temperatures near 20° F while the gas temperature was maintained high enough for rapid ice removal under more severe conditions. Heating requirements for the intermittently heated areas consequently were determined as the prime consideration, whereas the parting strip was permitted an increase in chordwise extent commensurate with the heat input in the supply duct. This practice resulted in a parting-strip width in the order of 1.5 to 3 inches at 20° F datum air temperature rather than the 0.5 to 1.0 inch obtained at 0° F.

In the range of conditions investigated, little effect of gas flow rate on parting strip width was observed. All the gas flows were sufficiently high to establish a large heat-transfer coefficient between the gas and the supply-duct wall; consequently, changes in the flow had only a small effect on the temperature differential between the gas and the duct wall, with the result that the amount of heat conducted by the fin to the parting-strip area was relatively independent of gas flow.

With cycle ratios in the order of 10, the equivalent continuous heat requirement for the intermittently heated areas is considerably greater than the heat required for the parting strip. With cycle ratios in the order of 20, the two heat requirements approach equality. At the higher cycle ratios, no appreciable decrease in the combined heat requirement can be expected unless a heat-off period greater than 260 seconds is used.

The chordwise parting strips performed satisfactorily; however, their chordwise extent (see table I) could be reduced, especially on the lower surface. The chordwise parting strips were useful near the leading edge when the ice formations were too thick to break readily during ice removal. By a reduction in the chordwise extent of these parting strips, the drop in supply-duct gas temperature would be reduced and more heat provided for cyclical de-icing.

SUMMARY OF RESULTS

The preliminary results obtained in an investigation of cyclical de-icing with a gas-heated airfoil are summarized as follows:

1. Satisfactory cyclical de-icing of an 8-foot chord NACA 65₁-212 series airfoil was achieved with a hot-gas system over a range of cycle ratios from 10 to 26 and utilizing a continuously gas-heated parting strip.
2. In the range of conditions investigated, the prime variables in the determination of the required heat input for cyclic ice removal were the datum air temperature and the cycle ratio; heat-off period, liquid-water content, airspeed, and angle of attack had only secondary effects on heat requirements.
3. For minimum runback, efficient ice removal, and minimum total heat input, short heat-on periods of about 15 seconds with heat-off periods of approximately 260 seconds gave the best results.
4. In general, the highest gas temperatures and flow rates usable for a given operating and icing condition resulted in the shortest heat-on periods and the best ice removal.

5. Representative data associated with good cyclical de-icing for a specific operating and icing condition are summarized as follows:

Airspeed, mph	280
Datum air temperature, °F	0
Liquid-water content, gram/cu m	0.6
Angle of attack, deg	5
Heat-on period, sec	15
Heat-off period, sec	260
Gas temperature at plenum chamber inlet, °F	467
Gas flow, lb/hr	800
Spanwise temperature drop in supply duct caused by parting strip, °F/ft of span	7
Cycle ratio	18.3
Equivalent continuous heat requirement for cycled areas, Btu/hr	1615

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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TABLE I - DIMENSIONS OF AIRFOIL MODEL



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Airfoil, NACA series	651-212
span, ft	6
chord, ft	8
maximum thickness, in.	11.5
Heated leading edge, extent, percent of chord	12
center segment span, ft	3
inboard and outboard segments, span, ft	1.5
Double-skin construction, inner-skin thickness, in.	0.040
outer-skin thickness, in.	0.025
inner-skin corrugations, pitch, in.	1.0
inner-skin passages, height, in.	0.12
inner-skin passages, width, in.	0.70
Spanwise parting strip, lower-surface location, percent of chord	1.0
fin thickness, in.	0.062
fin length, in.	3.5
fin material, aluminum	280
Chordwise parting strip, surface extent, top surface, in.	3
bottom surface, in.	6
fin thicknesses, top to bottom surfaces, in.	0.051, 0.062, 0.062, 0.051, 0.040, 0.025
fin lengths, top to bottom surfaces, in.	2.7, 3.0, 2.7, 1.7, 1.5, 1.3
Double-passage duct construction, center-line location, in. from nose	4.4
spanwise length, ft	5.8
material, aluminum	280
wall thickness, in.	0.094
cross-sectional area, front passage, sq in.	1.5
rear passage, sq in.	1.7
valve ports, sq in.	1.1
Plenum chambers, rear partition location, in. from nose	8
Asbestos sheeting, thickness, in.	0.030

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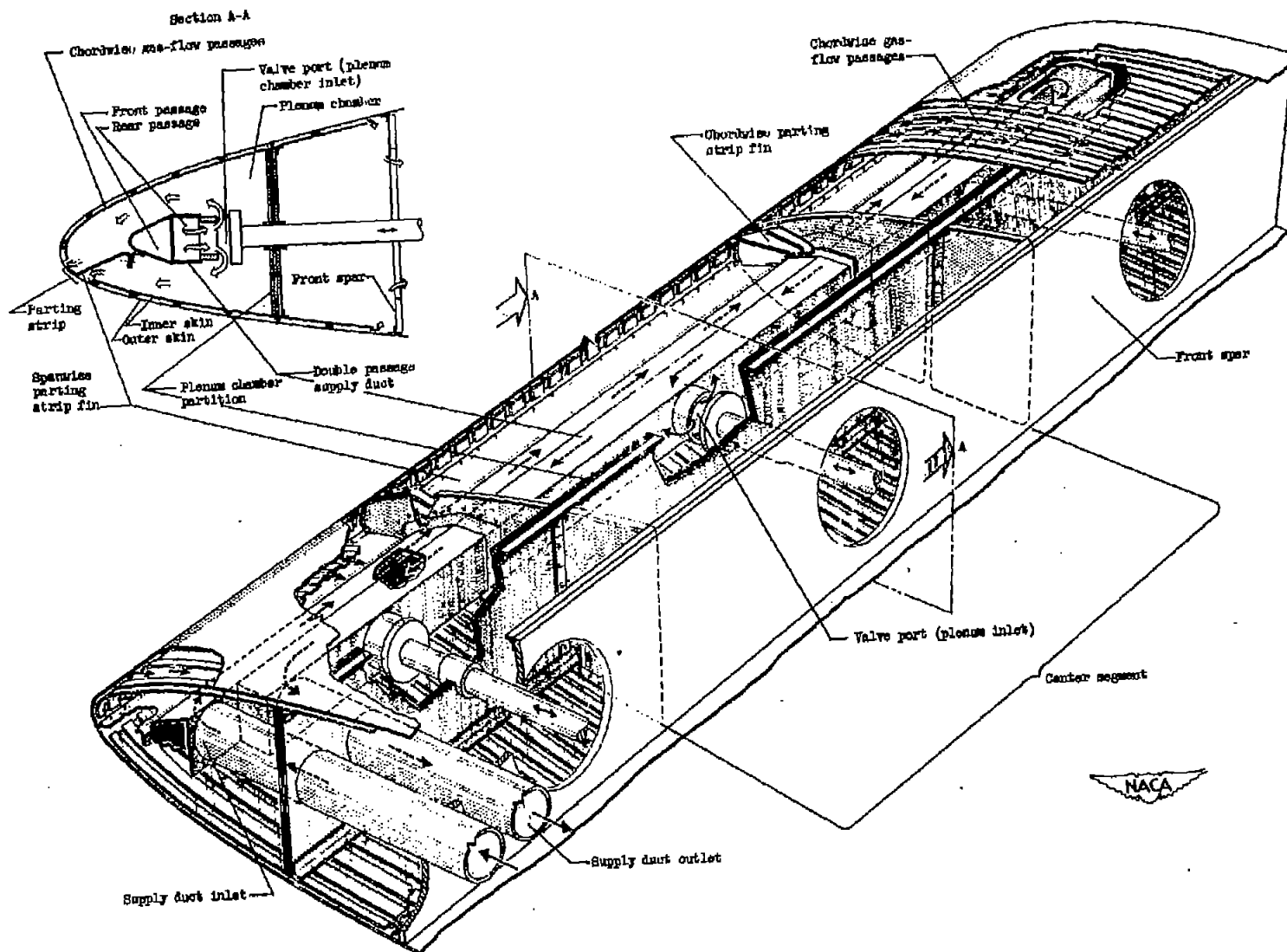
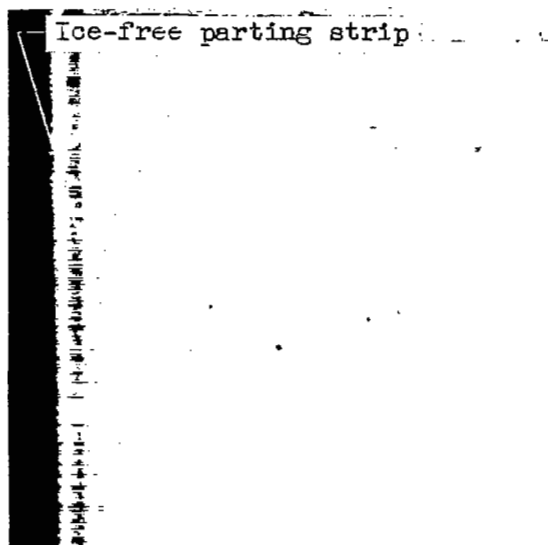


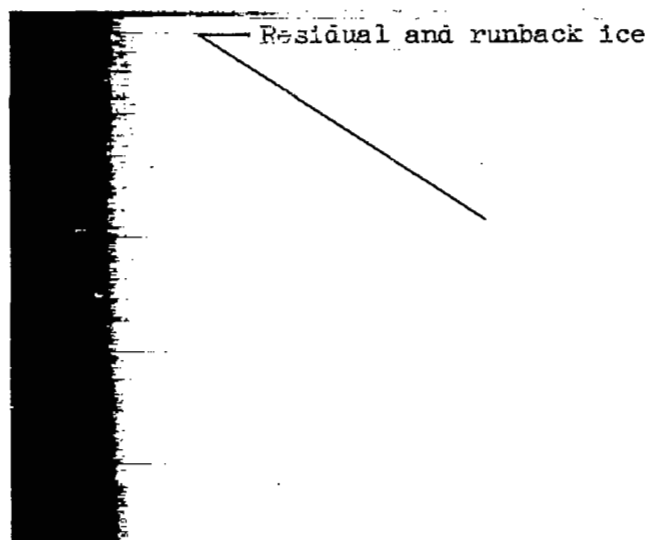
Figure 1. - Construction details of gas-heated airfoil for cyclical de-icing.



Figure 2. - Installation of airfoil model in 6- by 9-foot test section of icing research tunnel.

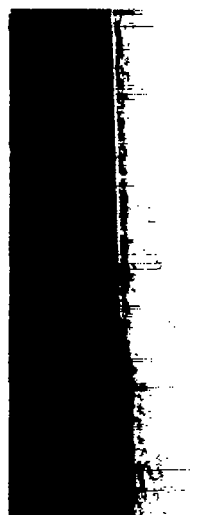


(a) Before heat-on period.



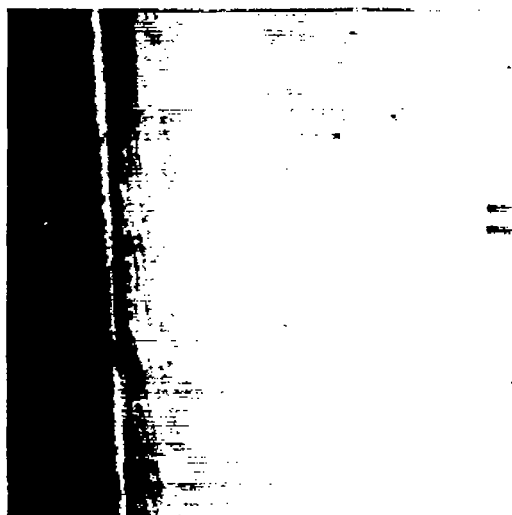
(b) After heat-on period.

Figure 3. - Characteristic ice formations on airfoil leading edge for design operating and icing conditions. Air speed, 280 miles per hour; datum air temperature, -4°F ; liquid-water content, 0.6 gram per cubic meter; angle of attack, 5° ; gas flow, 794 pounds per hour; supply-duct-inlet gas temperature, 500°F ; heat-on period, 15 seconds; heat-off period, 260 seconds; total icing time, 30 minutes.



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(a) After 15-second heat-on period. Icing time, approximately 5 minutes.



(b) Before heat-on period.

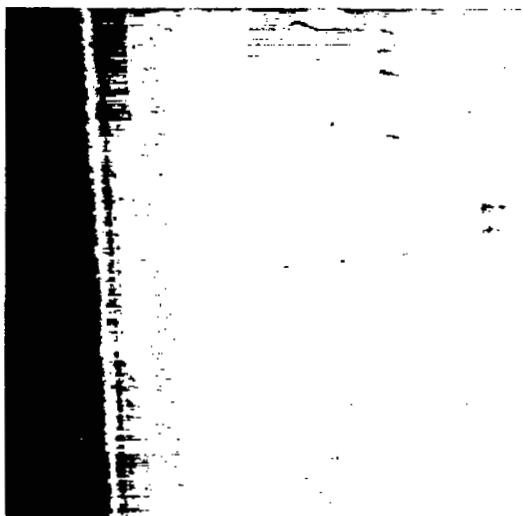
Icing time, approximately 11 minutes.



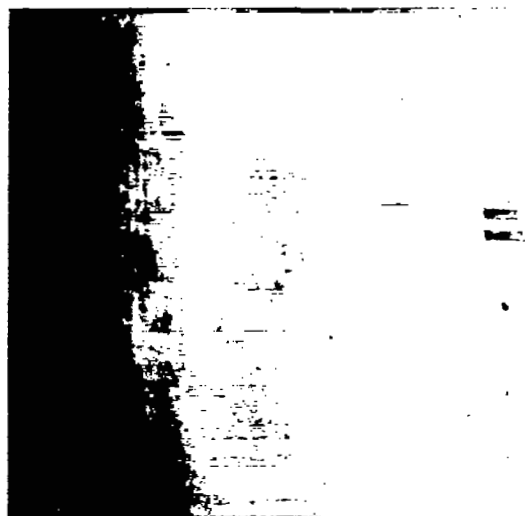
(c) After 15-second heat-on period.

Icing time, approximately 11 minutes.

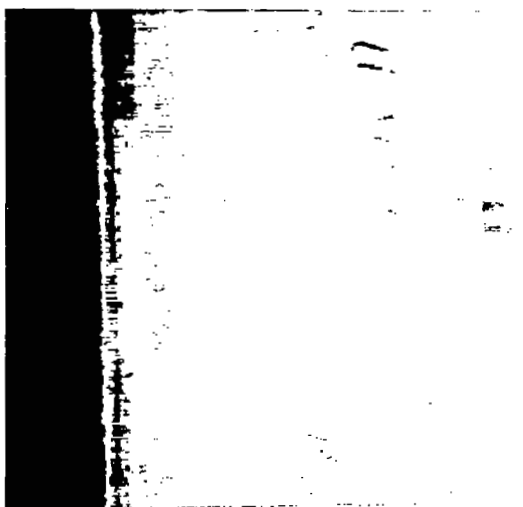
Figure 4. - Growth of runback and residual ice formations on the airfoil during cyclic de-icing. Air speed, 180 miles per hour; datum air temperature, 20° F; liquid-water content, 0.8 gram per cubic meter; angle of attack, 5° ; gas flow, 800 pounds per hour; model-inlet gas temperature, 250° F; heat-off period, 6 minutes.



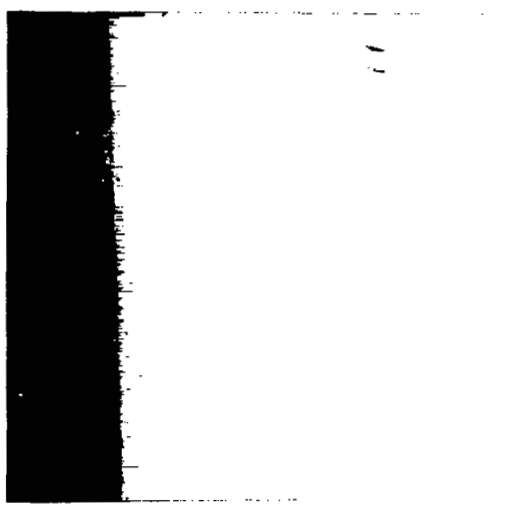
(d) Before heat-on period.
Icing time, approximately 18 minutes.



(e) After 15-second heat-on period.
Icing time, approximately 18 minutes.



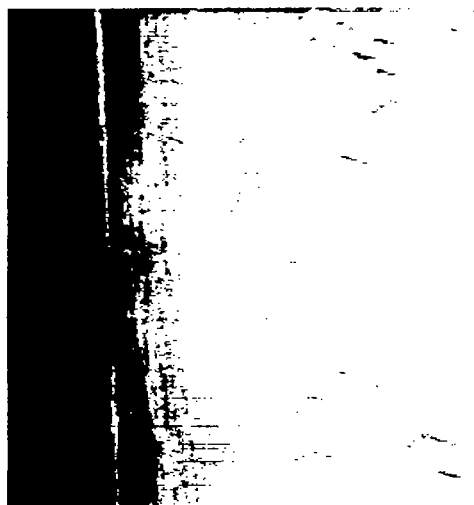
(f) Before heat-on period.
Icing time, approximately 24 minutes.



(g) After 15-second heat-on period.
Icing time, approximately 24 minutes.

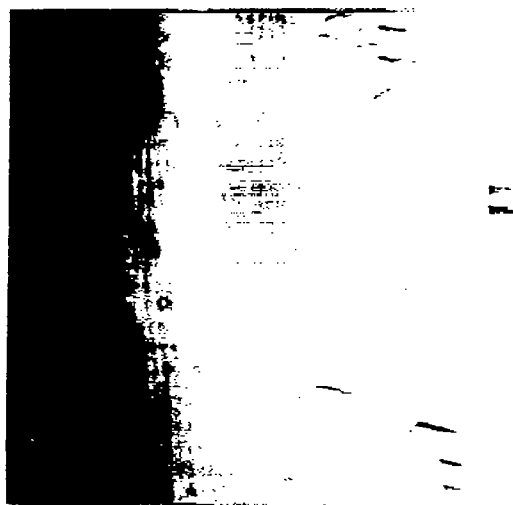
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Figure 4. - Continued. Growth of runback and residual ice formations on the airfoil during cyclic de-icing. Air speed, 180 miles per hour; datum air temperature, 20° F; liquid-water content, 0.8 gram per cubic meter; angle of attack, 5° ; gas flow, 800 pounds per hour; model-inlet gas temperature, 250° F; heat-off period, 6 minutes.



(h) Before heat-on period.

Icing time, approximately 38 minutes.



(i) After 15-second heat-on period.

Icing time, approximately 38 minutes.

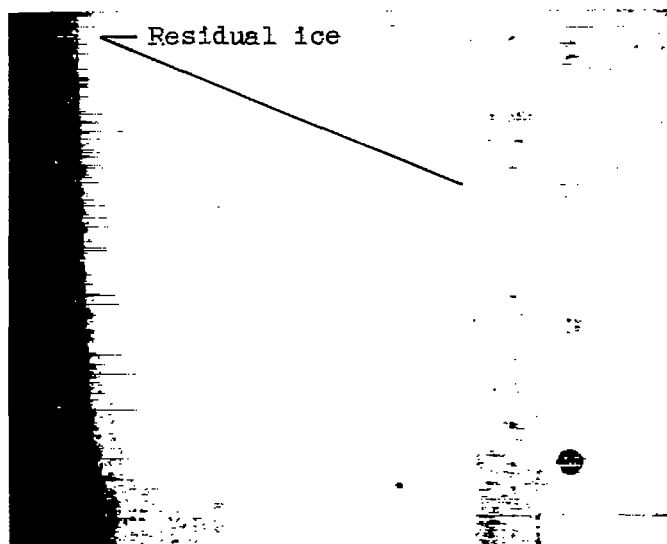


(j) After 20-second heat-on period. Icing time, approximately 51 minutes. Heat-on period changed to 20 seconds after 44 minutes of icing.

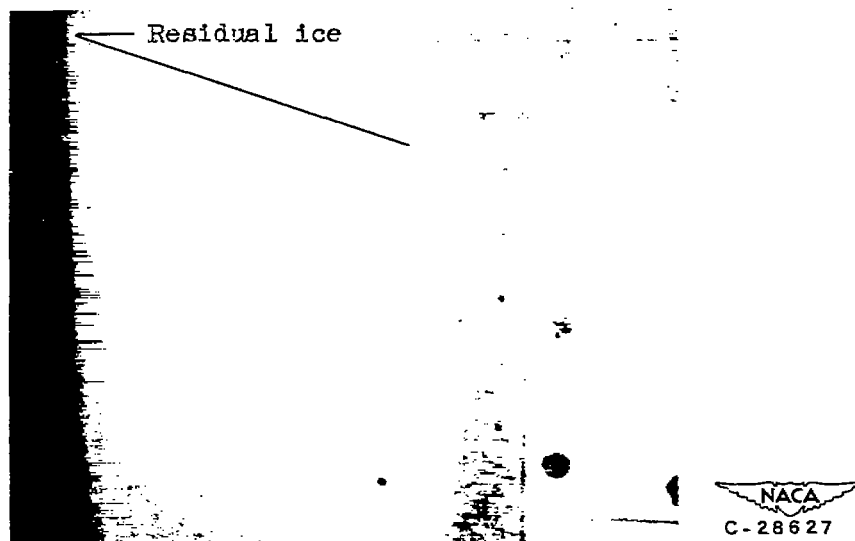
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Figure 4. - Concluded. Growth of runback and residual ice formations on the airfoil during cyclic de-icing. Air speed, 180 miles per hour; datum air temperature, 20° F; liquid-water content, 0.8 gram per cubic meter; angle of attack, 5° ; gas flow, 800 pounds per hour; model-inlet gas temperature, 250° F; heat-off period, 6 minutes.

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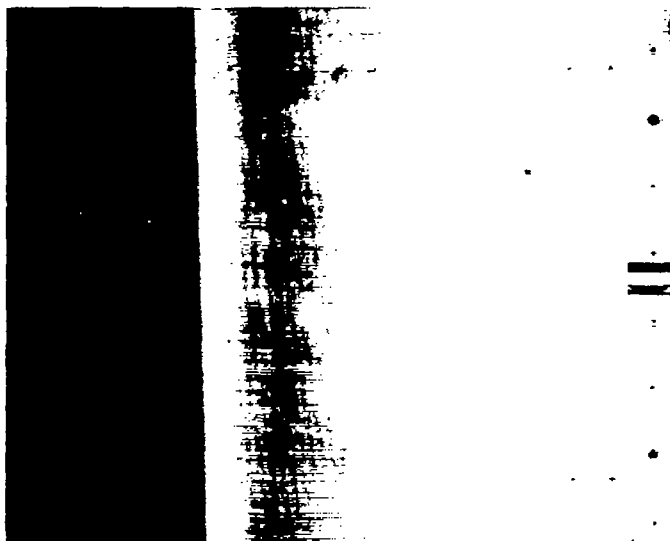


(a) Heat-on period, 20 seconds; icing time, 1 hour and 22 minutes.

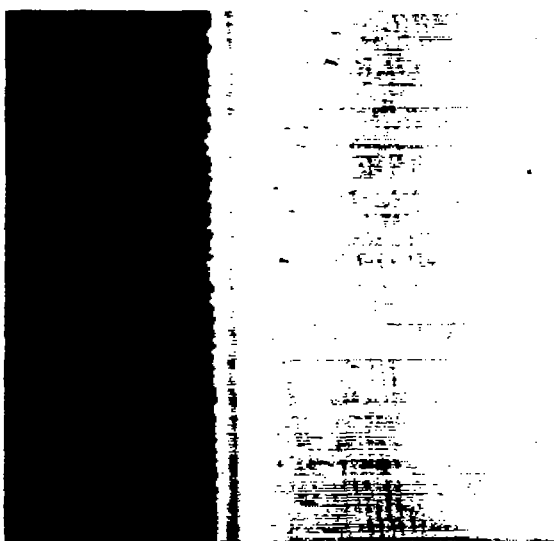


(b) Heat-on period, 15 seconds; total icing time, 1 hour and 55 minutes.

Figure 5. - Effect of heat-on time on residual ice formation. Air speed, 280 miles per hour; datum air temperature, 0° F; liquid-water content, 0.6 gram per cubic meter; angle of attack, 5° ; gas flow, 800 pounds per hour; model-inlet-gas temperature, 500° F; heat-off period, 6 minutes.



(a) Air speed, 180 miles per hour; datum air temperature, 0° F; angle of attack, $+2^{\circ}$; liquid water content, 0.6 gram per cubic meter; icing time, 6 minutes.



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(b) Air speed, 280 miles per hour; datum air temperature, $+20^{\circ}$ F; angle of attack, $+5^{\circ}$; liquid water content, 0.8 gram per cubic meter; icing time, 8 minutes.

Figure 6. - Ice formations on unheated airfoil.

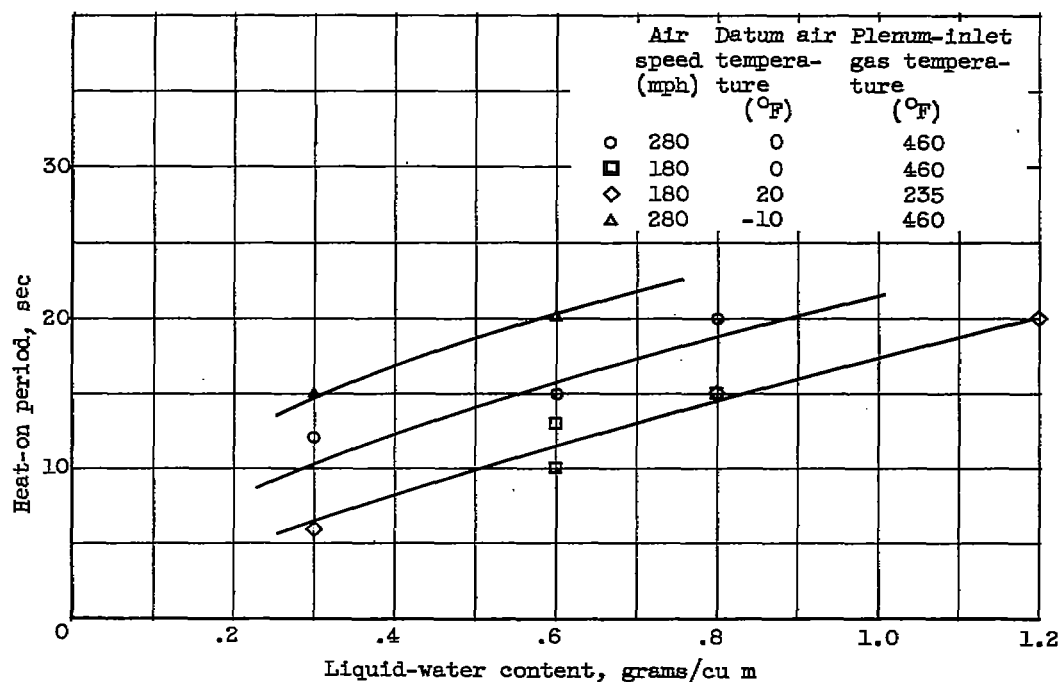


Figure 7. - Heat-on period as function of liquid-water content for several operating conditions. Gas flow, 800 pounds per hour; heat-off period, approximately 260 seconds.

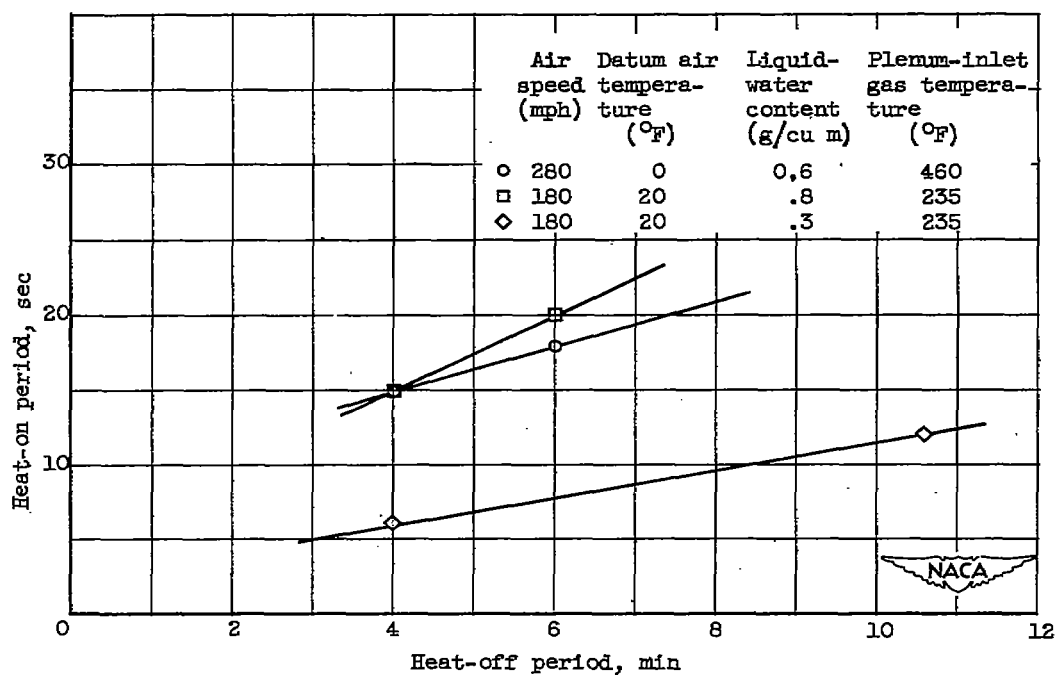


Figure 8. - Variation of required heat-on period with heat-off period for several operating conditions. Gas flow, 800 pounds per hour.

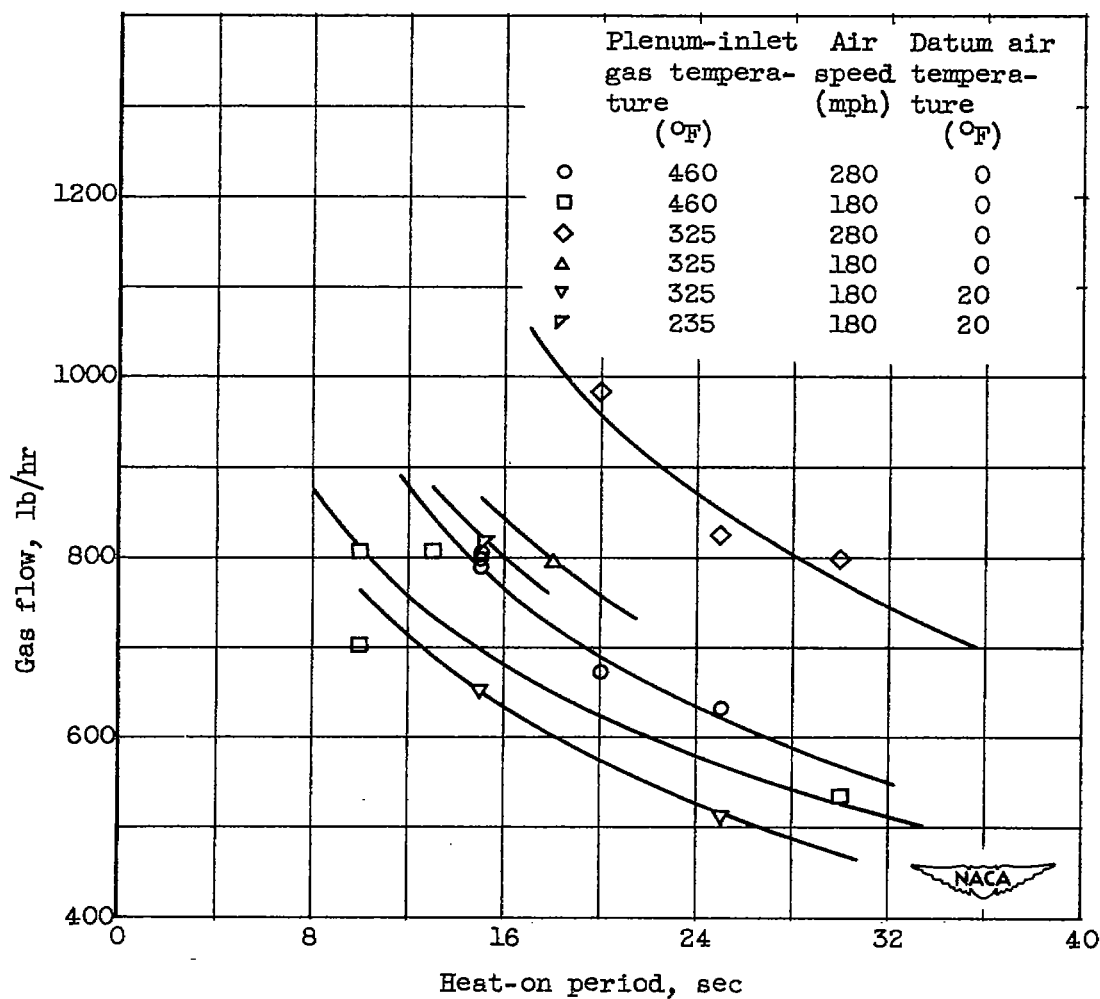


Figure 9. - Variation of gas flow with heat-on period for various air speeds, datum air temperatures, and plenum-inlet gas temperatures. Liquid-water content, nominal; heat-off period, approximately 260 seconds.

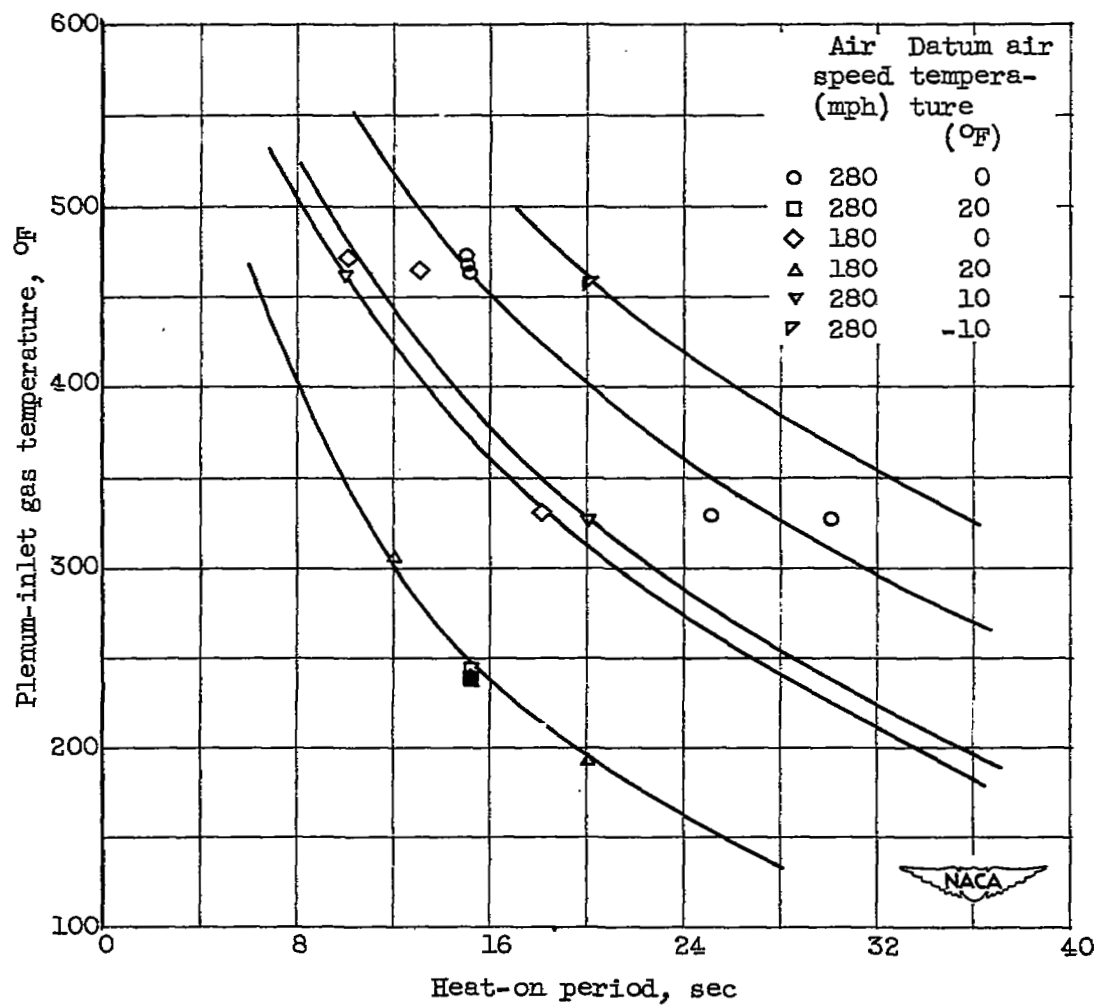


Figure 10. - Plenum-inlet gas temperature as function of heat-on period for two air speeds and various datum air temperatures. Liquid-water content, nominal; gas flow, 800 pounds per hour; heat-off period, approximately 260 seconds.

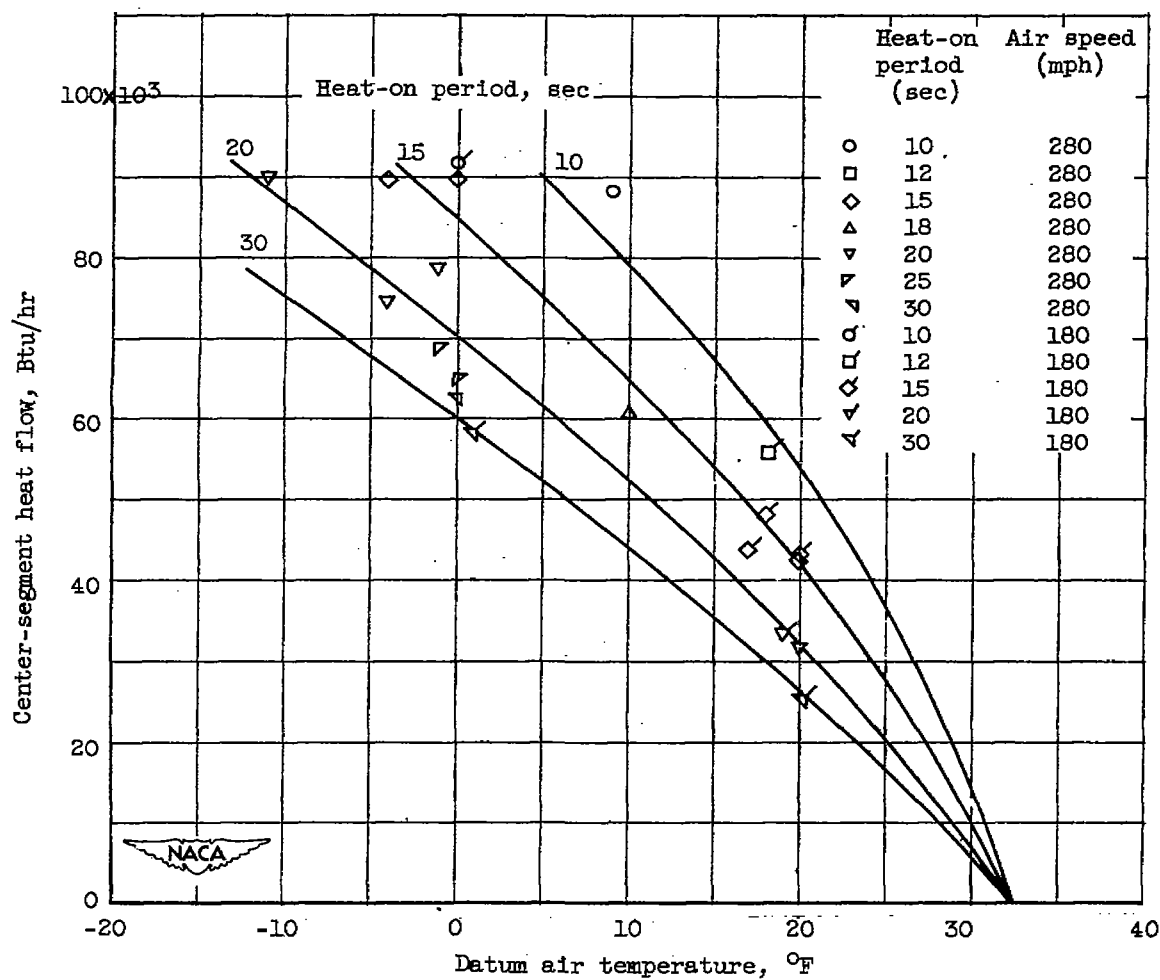


Figure 11. - Variation of center-segment heat requirement with datum air temperature for several heat-on periods and two air speeds. Liquid-water content, nominal; heat-off period, approximately 260 seconds.

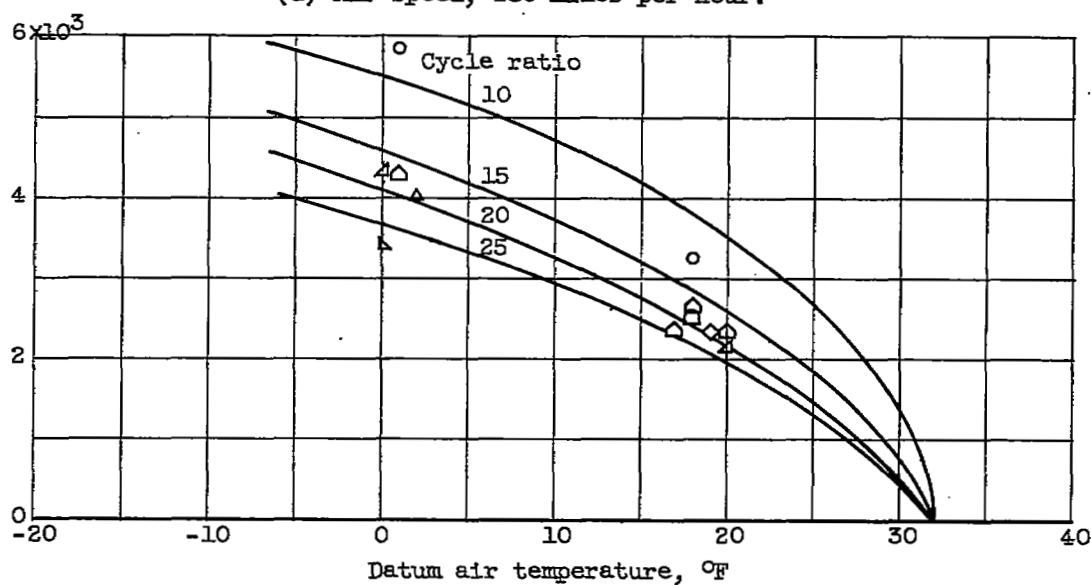
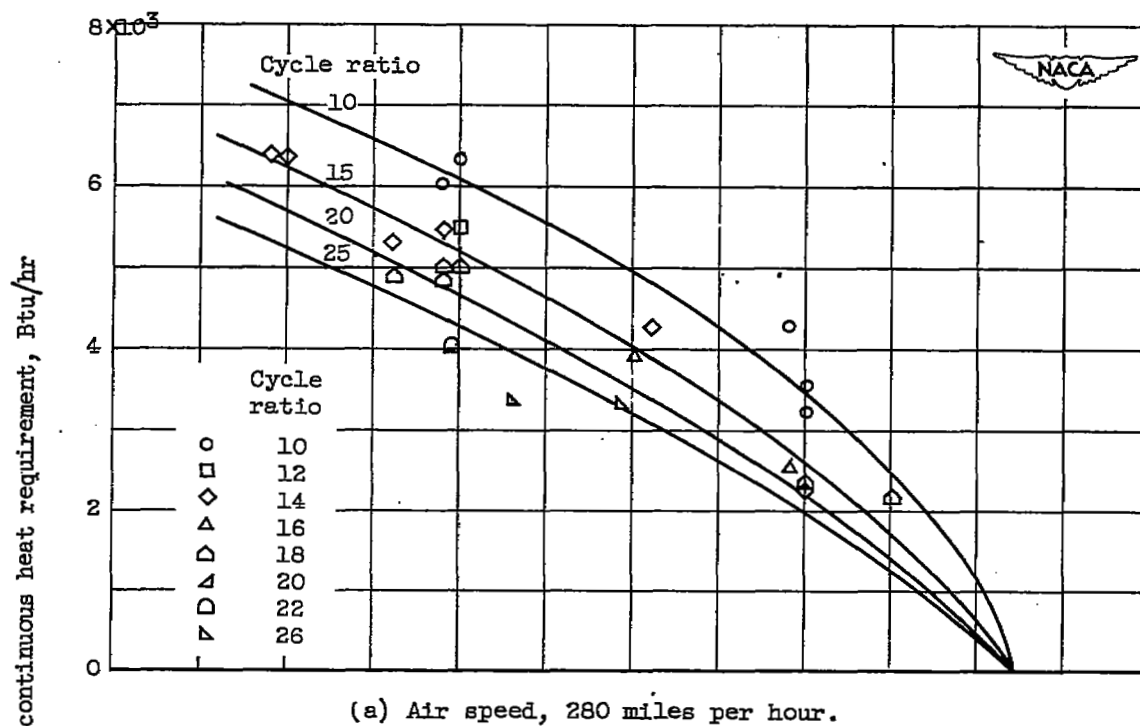


Figure 12. - Equivalent continuous heat requirement for center segment as function of datum air temperature for several cycle ratios. Liquid-water content, nominal.

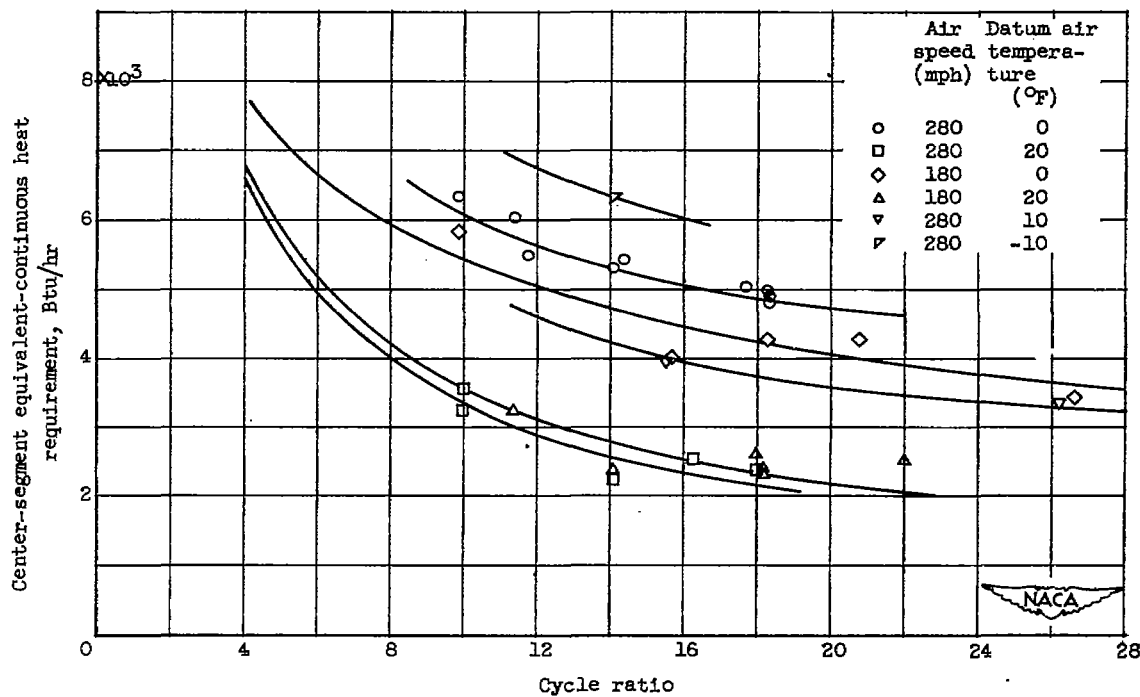
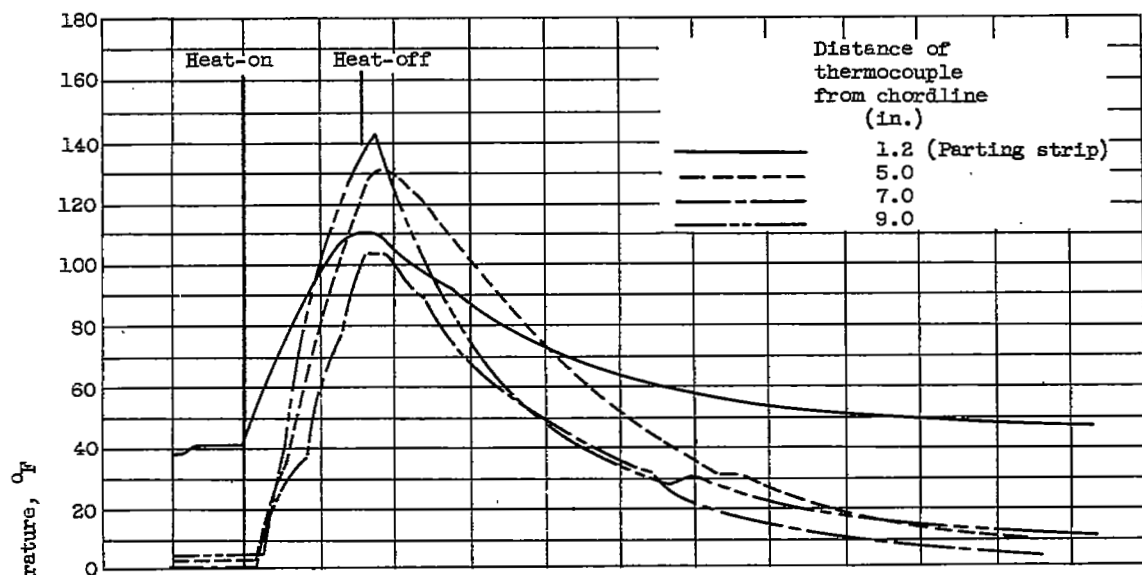
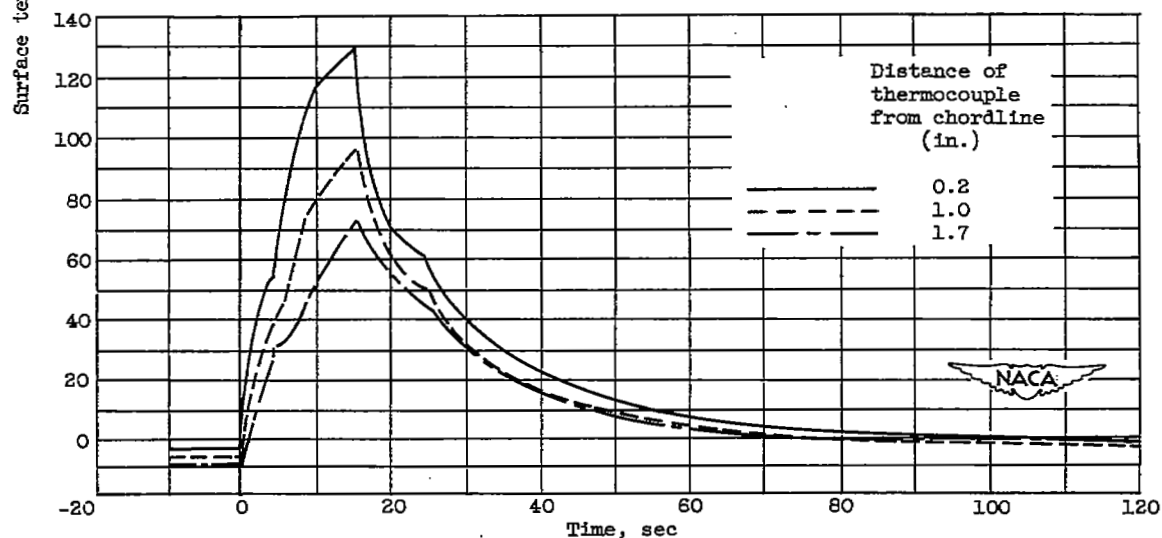


Figure 13. - Variation of equivalent continuous heat requirement for center segment with cycle ratio for two air speeds and several datum air temperatures. Liquid-water content, nominal; heat-off period, approximately 260 seconds.



(a) Lower surface.



(b) Upper surface.

Figure 14. - Variation of surface temperature during cyclic de-icing. Air speed, 280 miles per hour; datum air temperature, -4°F ; liquid-water content, 0.6 gram per cubic meter; gas flow, 800 pounds per hour; plenum-inlet gas temperature, 463°F ; heat-on period, 15 seconds; heat-off period, 260 seconds.

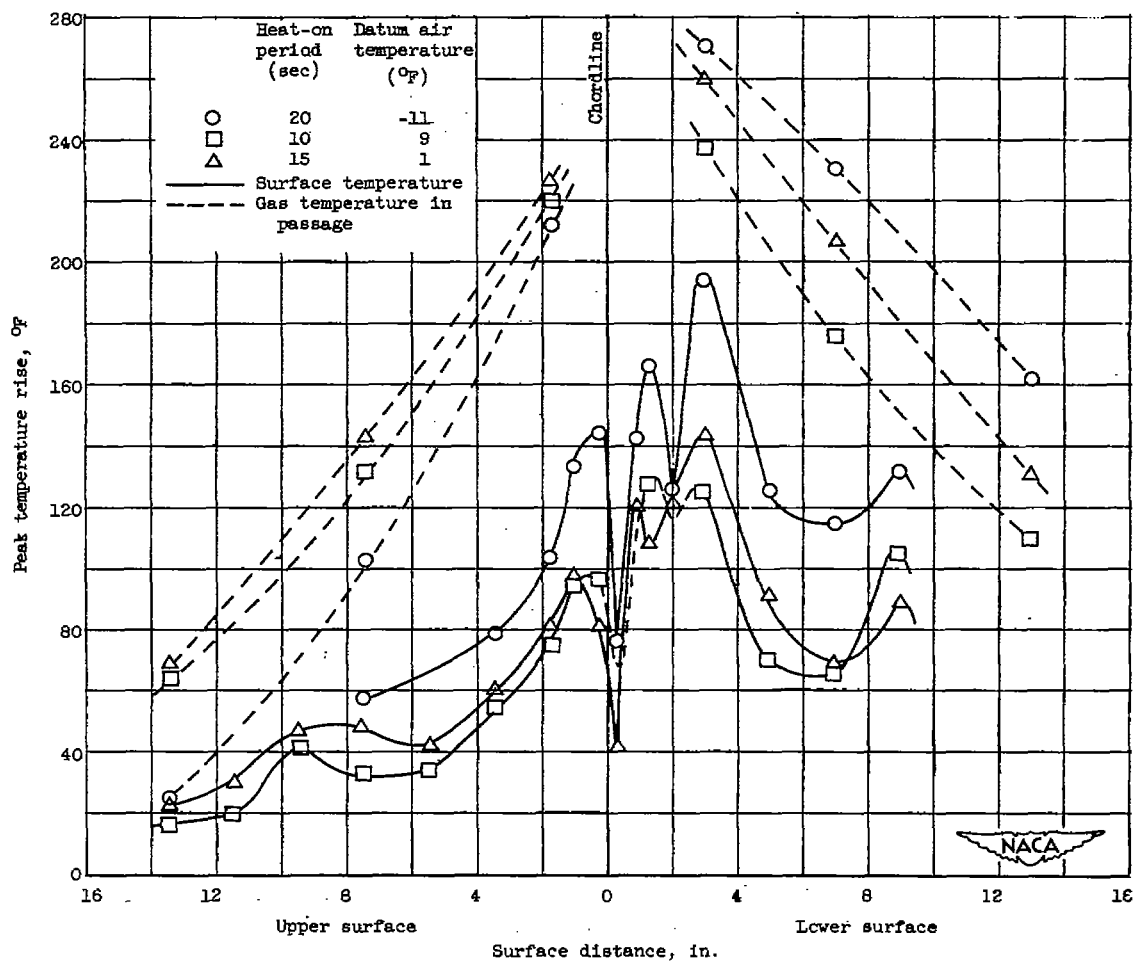


Figure 15. - Peak temperature rise during cyclic de-icing for various heat-on periods and datum air temperatures. Air speed, 280 miles per hour; liquid-water content, 0.6 gram per cubic meter; gas flow, 800 pounds per hour; plenum-inlet gas temperature, 460° F; heat-off period, approximately 260 seconds.

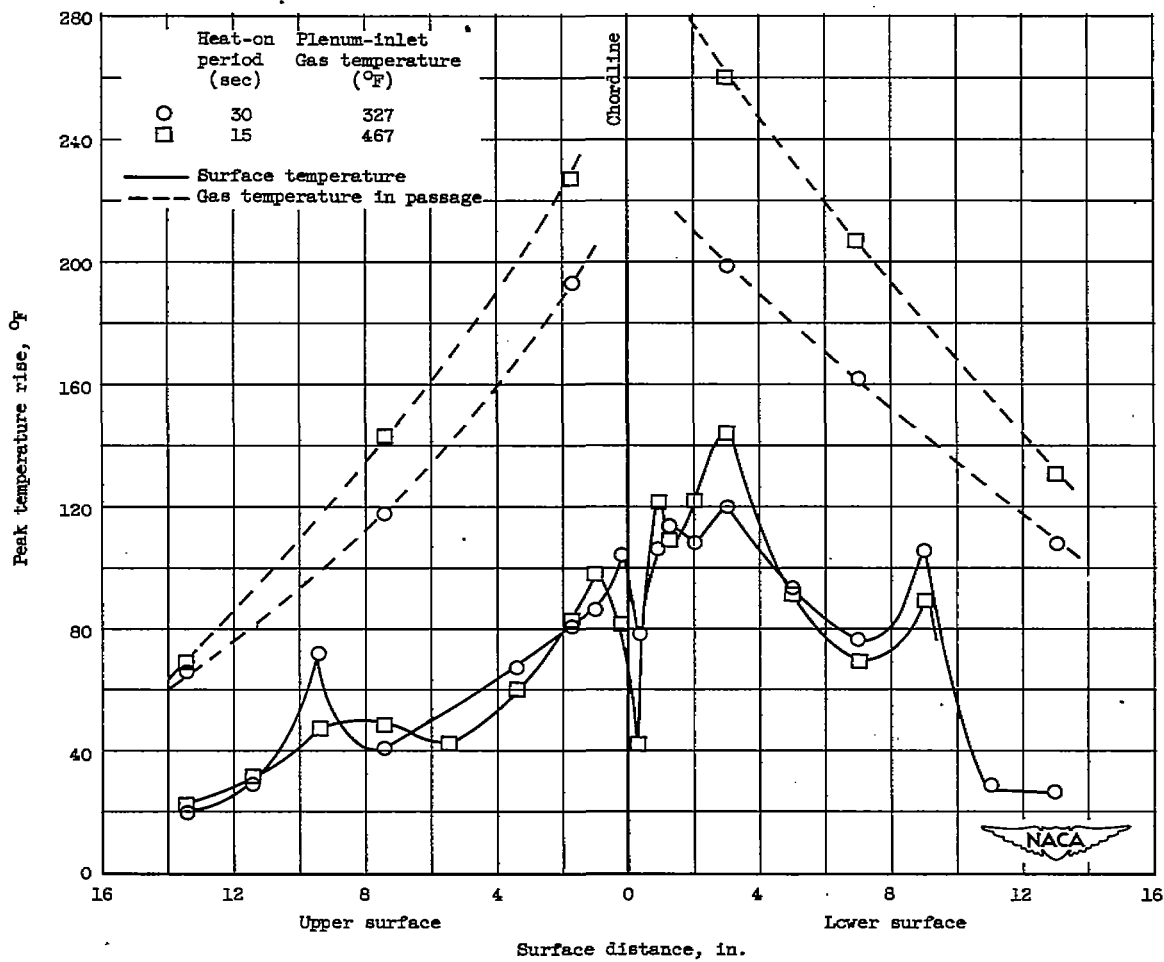


Figure 16. - Peak temperature rise obtained during cyclic de-icing with two combinations of heat-on period and gas temperature. Air speed, 280 miles per hour; datum air temperature, 0° F; liquid-water content, 0.6 gram per cubic meter; gas flow, 800 pounds per hour.

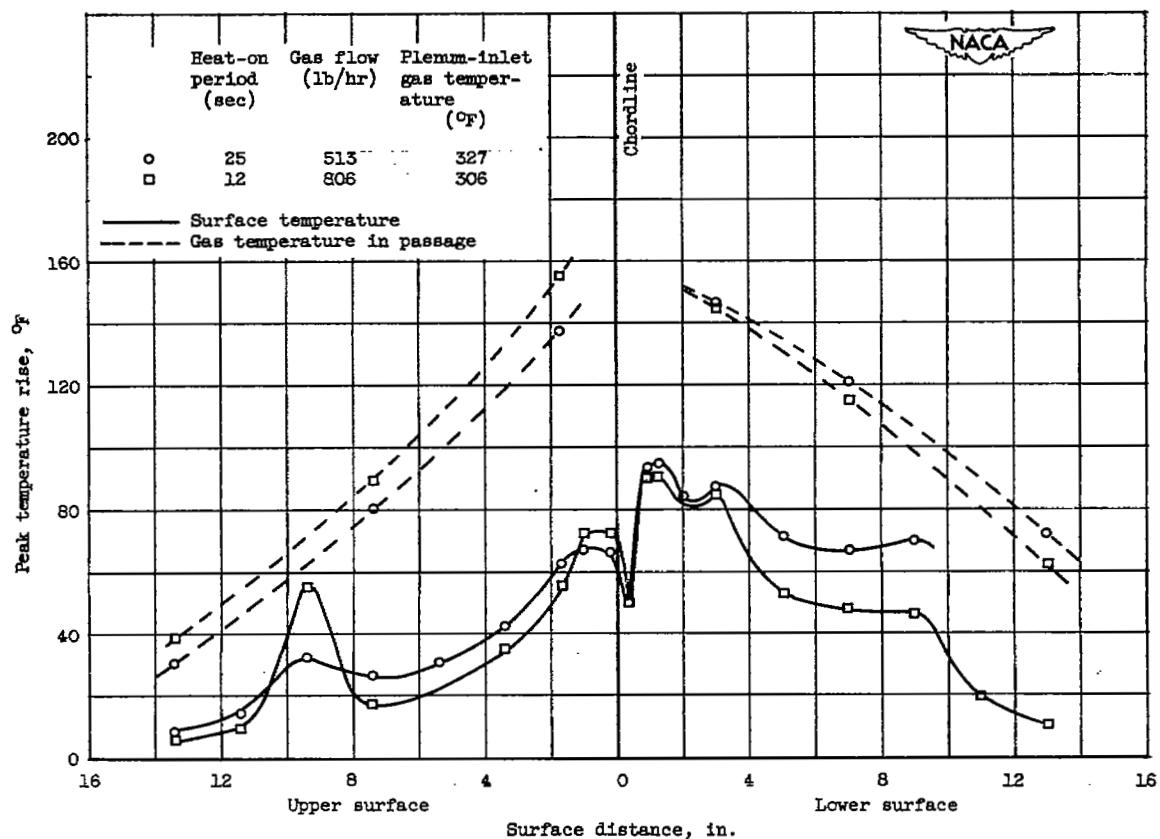


Figure 17. - Peak temperature rise during cyclic de-icing for two combinations of heat-on period and gas flow. Air speed, 180 miles per hour; datum air temperature, 18° F; liquid-water content, 0.8 gram per cubic meter; heat-off period, approximately 260 seconds.

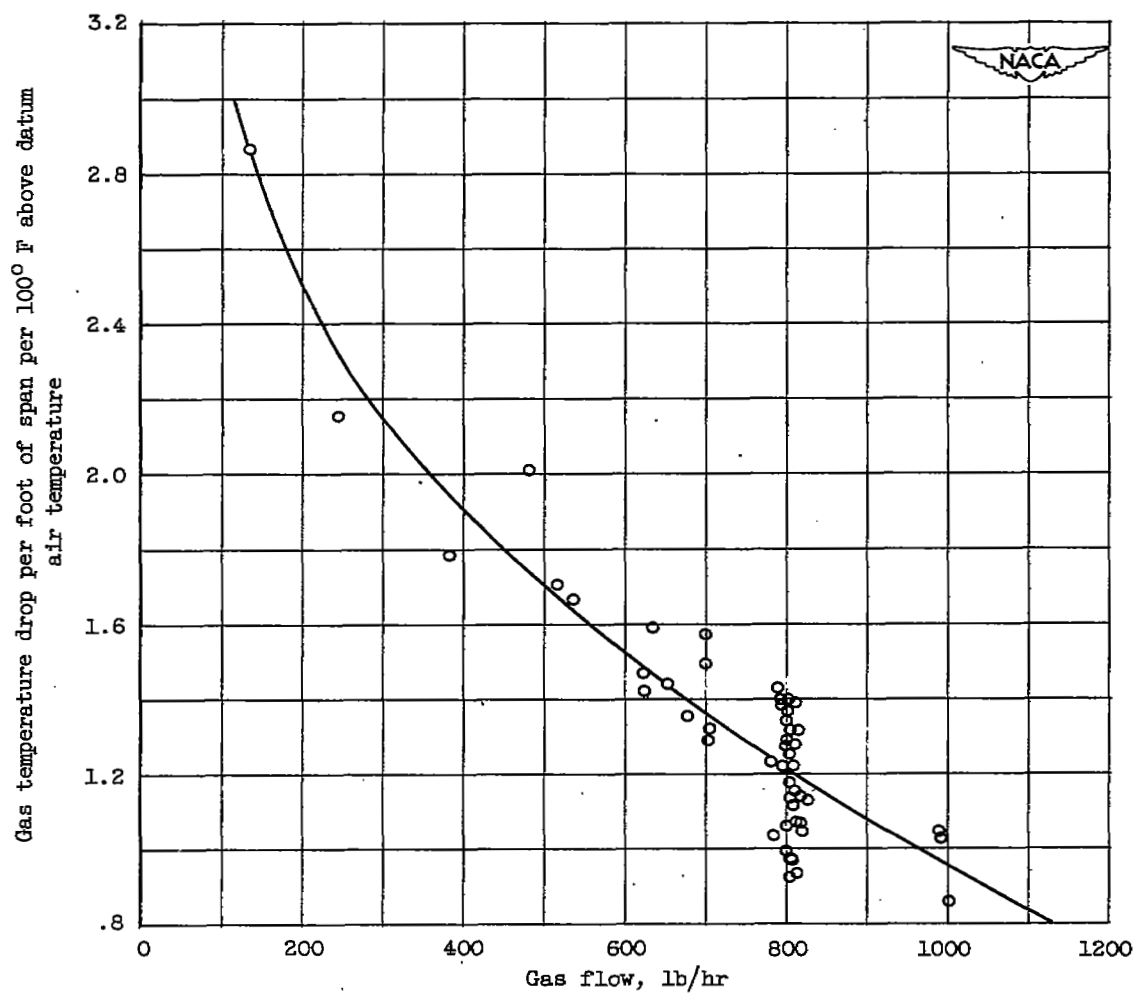
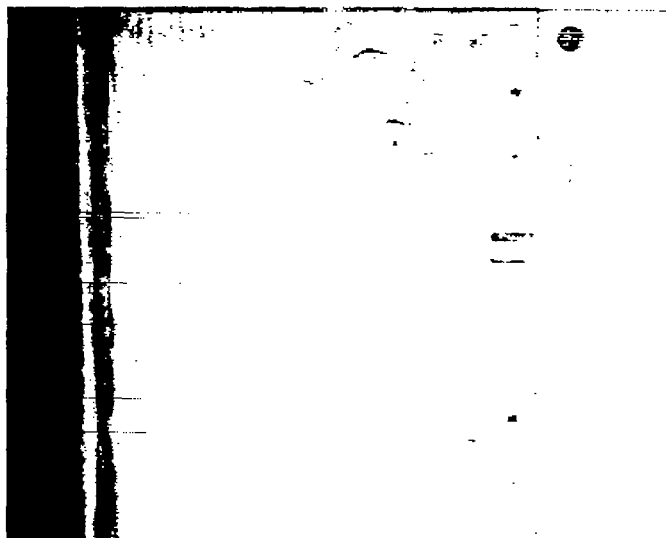
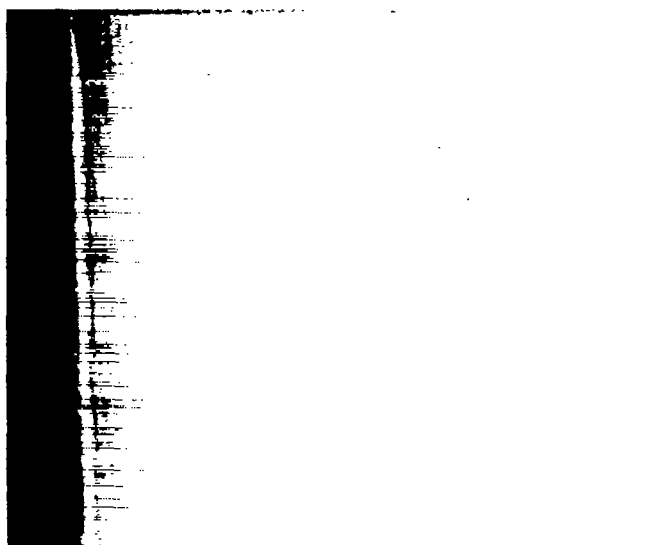


Figure 18. - Gas-temperature drop in double duct as function of gas flow and supply-duct-inlet gas temperature.



(a) Supply-duct-inlet gas temperature, 350° F.



(b) Supply-duct-inlet gas temperature, 500° F.

Figure 19. - Effect of gas temperature on width of parting strip. Air speed, 280 miles per hour; datum air temperature, 10° F; liquid-water content, 0.6 gram per cubic meter; angle of attack, 5°; gas flow, 800 pounds per hour; heat-off period, 260 seconds.

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